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GROUNDWATER SAPPING AND VALLEY DEVELOPMENT IN THE HACKNESS HILLS, NORTH YORKSHIRE, ENGLAND

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ABSTRACT

This paper describes evidence for the role of groundwater sapping and seepage erosion processes in the development of valleys which cut the southern edge of the Hackness Hills plateau in North Yorkshire, England. The development of drainage in this region has previously been suggested to relate to erosion by Late Devensian sub-aerial glacial meltwater channels. The role of groundwater erosion is investigated through a combination of geomorphological studies, lithological logging and X-ray diffraction (XRD) analyses.

The geology of the region consists of a series of permeable Middle and Upper Jurassic lithologies (the Corallian sequence and Lower Calcareous Grit) which overlie the impermeable Upper Oxford Clay. The rocks dip gently to the south at between 1° and 4° and are relatively unfolded. Valleys exhibit many characteristic features of groundwater sapping networks. They rise abruptly at the edge of the plateau with amphitheatre-like valley heads, alcoves in headwalls, steep bedrock side walls, flat floors, spring sites and seepage zones in many valley flanks.

Lithological logging indicates that sites of groundwater emergence usually occur either at or slightly above the boundary of the Upper Oxford Clay and Lower Calcareous Grit. XRD analyses of bedrock samples indicate that seepage occurs within siltstones which contain no clay but a variable percentage of calcite. The cause of groundwater emergence is attributed to decreasing grain size and increasing calcite cementation within bedrock which combine to reduce permeability. Development of valleys in the Hackness Hills is suggested to have occurred by a combination of headward erosion by groundwater sapping processes operating in an up-dip direction superimposed onto a valley morphology shaped by surface fluvial erosion.

KEY WORDS groundwater sapping; groundwater seepage; valley development; Hackness Hills; North Yorkshire

INTRODUCTION

The role of groundwater as an erosive agent, particularly through the operation of processes such as groundwater seepage and groundwater sapping (Higgins, 1984), has been increasingly recognized as an important factor in the formation of major landscape features such as valleys (for recent summaries see Baker, 1990; Uchupi and Oldale, 1994). Terrestrial valleys suggested to have been formed by groundwater erosion have been identified across a wide range of climatic settings, including systems in Hawaii (e.g. Baker, 1980; Kochel and Piper, 1986), the Colorado Plateau (e.g. Pieri *et al.*, 1980; Laity, 1983; Laity and Malin, 1985; Howard *et al.*, 1988), Massachusetts (Uchupi and Oldale, 1994), Japan (Onda, 1994), Libya (Peel, 1941), Egypt (Maxwell, 1979; El Baz *et al.*, 1980), New Zealand (Schumm and Phillips, 1986) and Botswana (Shaw and de Vries, 1988; Nash, 1992, 1995; Nash *et al.*, 1994a,b).

To date, however, with the exception of the postulated role of spring sapping in the development of dry valleys in the Cretaceous Chalk of southern England (e.g. Sparks and Lewis, 1957–8; Small, 1964), groundwater seepage and sapping processes have not been identified as a significant factor in the formation of British valleys. This paper aims to redress this imbalance by presenting the first study of valley development in the Hackness Hills and, through an analysis of the links between lithological variation and valley morphology, suggests that groundwater sapping processes played a major role in valley formation. As

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such, this study aims to broaden our knowledge of groundwater erosion processes, particularly in humid temperate areas which are generally less well understood than more arid regions. The emphasis of the present study is predominantly morphological and is intended to provide a basis for future process-oriented investigations.

REGIONAL SETTING

The Hackness Hills are particularly well known to British geologists as they were the subject of one of the first large-scale geological mapping surveys in Britain by William Smith (the 'Father of English Geology') in 1829. The area is located approximately 10 km northwest of Scarborough, North Yorkshire, on the eastern edge of the North York Moors National Park (Figure 1). Mean average annual rainfall for the area is 893 mm, with the highest monthly mean rainfall of 96 mm in November and December, and the lowest of 62 mm in July (data for the period 1950–1986 from Silpho Moor gauging station situated at 203 m above sea level, 54°20′15″N, 0°32′00″W). The hills consist of a broad plateau at 160 to 220 m above sea level bounded by escarpments to the north and east, the Lang Dale Valley containing the River Derwent to the west, and the Hackness Valley to the south. The plateau is cut by a series of steep-sided valleys, Whisperdales, High and Low Dales, which are incised by up to 70 m into the plateau surface. The streams draining

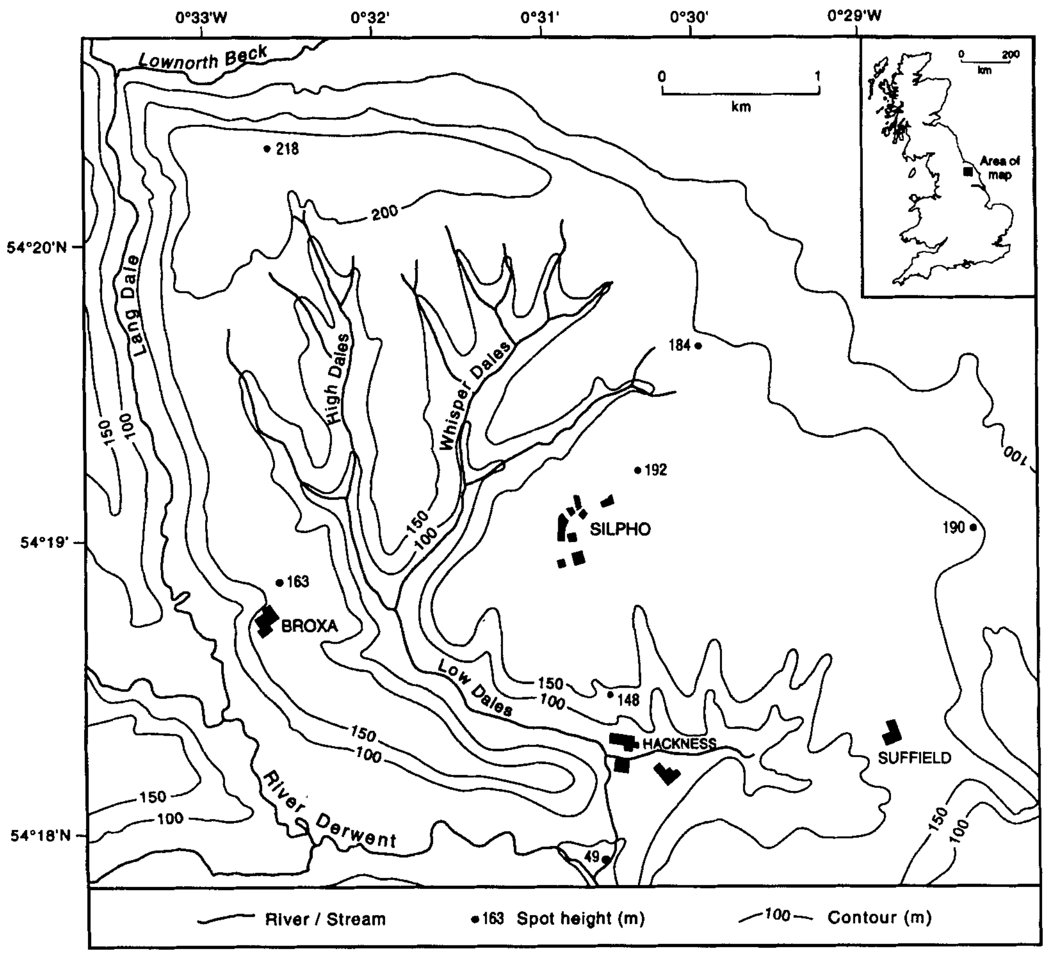

Figure 1. Location of the Hackness Hills

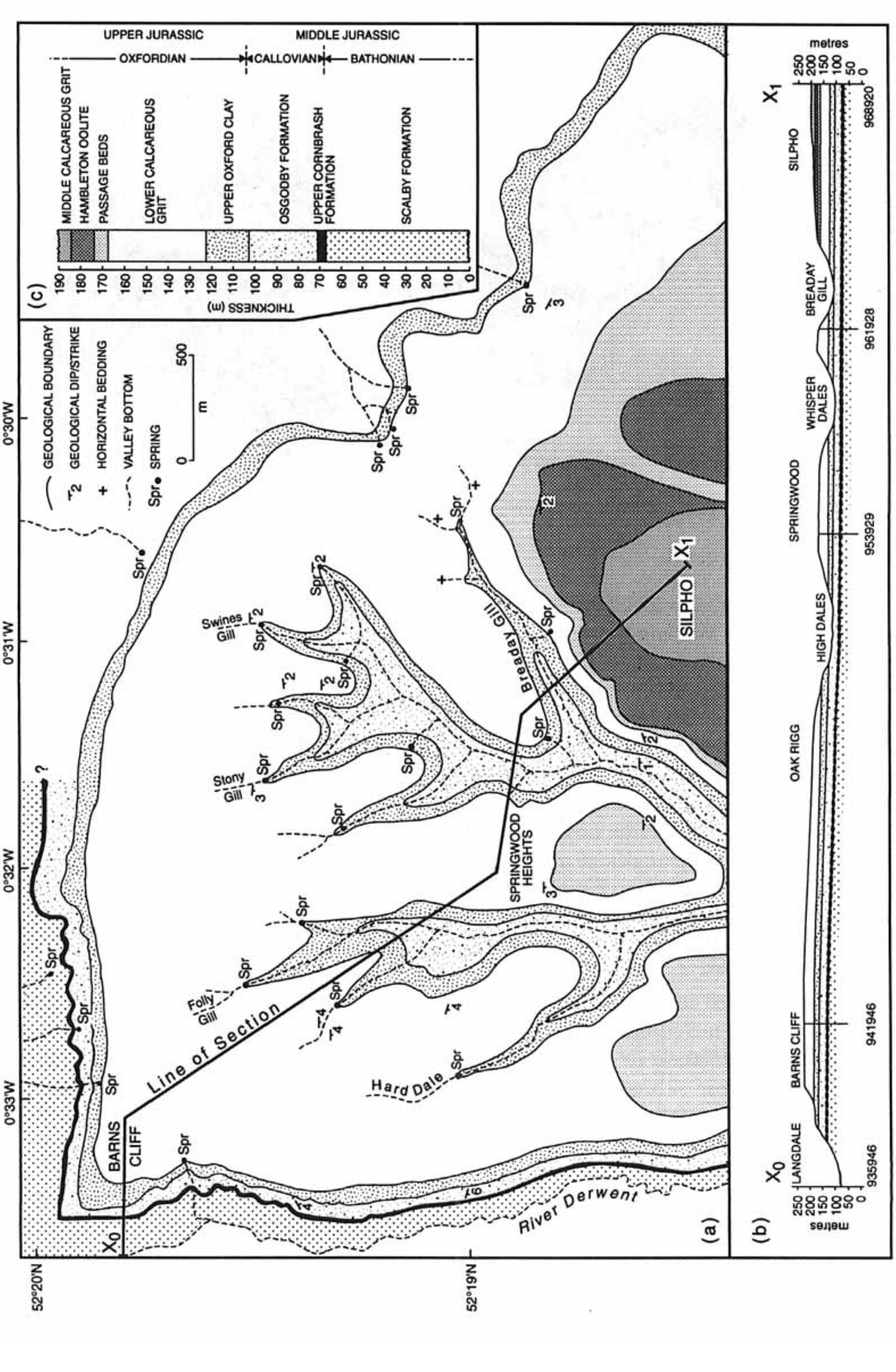

Figure 2. The geology of the Hackness Hills: (a) geological map; (b) representative cross-section; (c) total stratigraphic succession in the area of study

Figure 3. Looking south down High Dales from the nab separating Folly Gill and Oak Rigg Gill

these valleys are referred to locally as 'gills'. The centripetal drainage pattern of the hills is highly distinctive and was described by William Smith as being 'like the branching of a stag's horn' (Smith, 1829).

Geologically, the area is an outlier of Middle and Upper Jurassic shallow- to deep-water marine limestones, sandstones, siltstones and clays (Wilson, 1934, 1948; Arkell, 1933; Wright, 1968, 1972, 1983). The geological structure of the Hackness area is unusual within the British Isles as the rocks are relatively unfolded and almost horizontally bedded, dipping gently towards the south at angles of up to 4°. The stratigraphic sequence in the area, together with a geological cross-section, are shown in Figure 2. The influence of geology upon the topography of the area is particularly striking (Fox-Strangways, 1892; Brumhead, 1979), with the more resistant rocks (the Lower Calcareous Grit and various Corallian lithologies) forming escarpments or 'nabs' with slope angles of up to 35° compared with much gentler slopes on the softer lithologies such as the Upper Oxford Clay (Figure 3).

In addition to its geological interest, the Hackness region has also attracted the attention of geomorphologists because of the influence of the glacial history of the area upon drainage development (Kendall, 1902; Kendall and Wroot, 1924; Penny, 1974). Work in the early twentieth century envisaged a series of Late Devensian ice-dammed lakes in northeast Yorkshire (Kendall, 1902). The morphology of many of the valleys in the region, including the Hackness Gorge and Newtondale (to the west of the study area), has been attributed to formation by meltwater draining these pro-glacial lakes. The existence of many of these lakes has, however, been subsequently discounted, although there is evidence that a lake once occupied the Vale of Pickering to the south of the study region and that Newtondale may have once been a sub-aerial meltwater channel (Penny, 1974).

PROCESSES OF VALLEY DEVELOPMENT BY GROUNDWATER SAPPING

The role of groundwater processes in the origin of Whisperdales and High Dales has been recognized since at least 1924 when Kendall and Wroot noted the following in their classic text '*The Geology of Yorkshire*':

> The plateau is deeply incut with a series of very deep, well wooded valleys—the Whisperdales and the High and Low Dales—which in the mode of their formation are unique so far as this country is concerned. To understand their existence we must notice that the Coralline rocks are exceedingly pervious to water, but they overlie the impervious Oxford

> Clay. Rain falling upon the plateau consequently gives rise to springs which break out at the junction of the two series and have fed little streams. This action has been in operation in the production of the Whisperdales and its sister streams. Gradually the springs have cut farther and farther back into the desk-plateau until in plan they almost resemble a hand with outstretched fingers.
>
> (Kendall and Wroot, 1924, p.513)

This is probably the earliest direct reference to the potential role of groundwater seepage erosion in the formation of valleys. The idea had previously been attributed to Peel (1941) based upon observations in the Gilf Kebir plateau of Libya. In this region he identified wadis with flat floors and steep sides which terminated in a headward cliff and appeared to have been 'cut out from below' rather than 'let down from above'. This description succintly summarizes the key difference between erosion by exfiltrating water and the operation of surface incision by river erosion, namely that seepage erosion effectively undermines valley heads and sides due to enhanced weathering and erosion within a zone of groundwater emergence, as opposed to erosion by water flowing at the surface (Laity and Malin, 1985).

Three processes of groundwater erosion can be recognized: tunnel scour, sapping and seepage (Dunne, 1980, 1990; Higgins, 1984). Of these three, groundwater sapping and seepage erosion appear to be the most significant in terms of valley formation (Uchupi and Oldale, 1994), with tunnel scour being most effective at a smaller scale in the initiation of channels (Dunne, 1980). On the basis of studies on the Colorado Plateau, Howard *et al.* (1988) suggest five factors necessary for seepage erosion processes to operate. These requirements include the need for a permeable aquifer of a transmissive rock type, a rechargeable groundwater system (ideally of a large areal extent), a free face at which water can emerge, a structural or lithological inhomogeneity to increase local hydrologic conductivity, and a means of transporting material from the free face.

Valleys developed by sapping and seepage erosion are suggested to have a number of distinctive morphological features which, to a certain extent, may be diagnostic of the operation of groundwater processes in their formation (Howard *et al.*, 1988; Baker, 1990). These include abrupt valley initiation with amphitheatre headwalls and little evidence of surface flow above the valley head, alcoves and springs in the headward region, steep valley flanks with an abrupt angle to a flat valley floor, a long valley with a constant valley width, short first-order tributaries with possible hanging valleys and a paucity of tributaries downstream.

Field observations of groundwater erosion processes are extremely difficult, primarily owing to the problems of accessibility at headwalls of active gullies and streams. As a result, field studies of such processes are limited (see Onda, 1994, for a notable exception) and most quantitative assessments of the role of sapping and seepage erosion in valley development have come from experimental work using stream tables (e.g. Kochel and Piper, 1986; Howard and McLane, 1988, Gomez and Mullen, 1992). These experimental approaches use unconsolidated or semi-consolidated sediments to allow the rapid development of groundwater sapping features and are, as such, relatively limited in terms of their applicability to valley development in bedrock settings. Differences in experimental technique, particularly in the variety of initial conditions used in stream table experiments, also limit the detailed conclusions of these studies. Some general observations can, however, be made on the operation of sapping and seepage erosion processes.

The process of seepage erosion in bedrock involves at least some intergranular flow, with weathering proceeding by the slow release of grains at the point of groundwater emergence. Sapping and seepage are terms which are often used interchangeably, although strictly speaking, sapping should be confined to situations where groundwater emerges at spring sites (Higgins, 1984; Dunne, 1990). Experimental studies show that the main method of drainage network development by sapping is through headward erosion, which proceeds rapidly during the early stages of valley formation (Kochel *et al.*, 1985; Gomez and Mullen, 1992). Headward erosion occurs most effectively in gently dipping lithologies (1° to 4°), with erosion proceeding in an up-dip direction (Howard *et al.*, 1988). In cohesionless sediment, seepage forces at the site of emergence of sub-surface flow are most important controls on headward erosion (Howard and McLane, 1988) whereas in cohesive bedrock, mechanical and chemical weathering are likely to be the dominant displacive processes (Laity *et al.*, 1980). Tributary growth occurs as a result of permeability variations (Howard *et al.*, 1988) and disturbances in sub-surface flow (Dunne, 1980) and may also be influenced by joints and geological structures (Laity *et al.*, 1980; Pieri *et al.*, 1980; Laity, in Baker, 1990).

VALLEYS IN THE HACKNESS HILLS

Valley morphology

The tributary valleys feeding into Whisperdales and High Dales show many of the characteristics typical of valleys developed by sapping and seepage erosion described above, but also exhibit some significant differences. The most prominent similarity is that valleys rise abruptly on the plateau surface, often with an amphitheatre valley head and little evidence of surface drainage. The valley headwalls contain well-developed alcoves and may expose up to 12 m of vertical bedrock (in the case of the valley head of Breaday Gill). Figure 4 shows the headward end of Oak Rigg Gill (west of Folly Gill on Figure 2), where recent clearance of part of the coniferous forest which covers much of the northern Hackness Hills allows the abrupt change in slope morphology to be identified. The plateau surface is comparatively flat but there is a distinct convex slope downwards towards vertical outcrops of rock in the amphitheatre head region of the valley. In cross-section, valleys exhibit a gorge-like morphology (Figures 5 and 6) with the valley flanks consisting either entirely of vertical cliffs of Lower Calcareous Grit or, in the majority of cases, bedrock outcropping as low cliffs above steep debris slopes. In the upper sections of most tributaries the valley floor is relatively flat, although many tributaries exhibit abrupt steps in their long profile, associated with the presence of more indurated bedrock horizons.

Valleys can be divided morphologically and hydrologically into two zones in relation to spring sites which

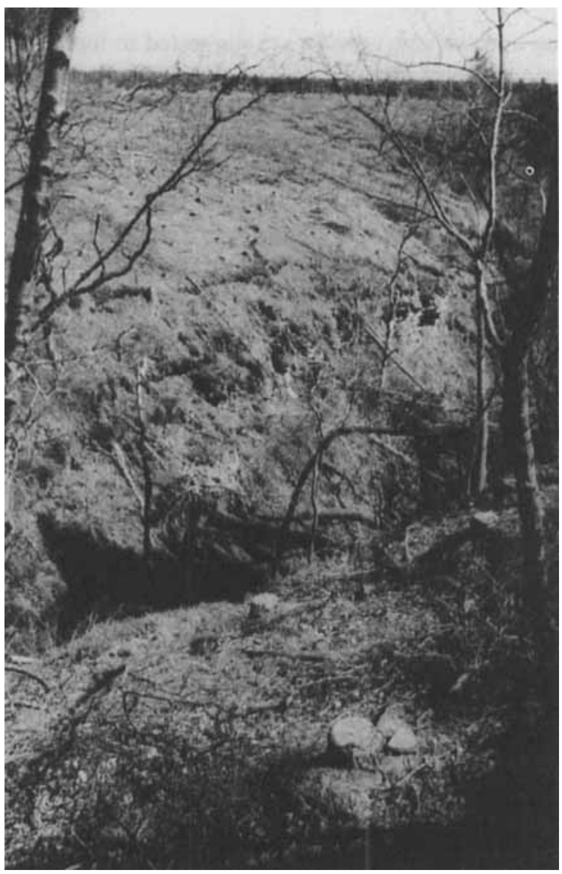

Figure 4. The valley head of Oak Rigg Gill (looking due east) showing the abrupt change in slope morphology between the plateau surface of the Hackness Hills and the steep-sided valley

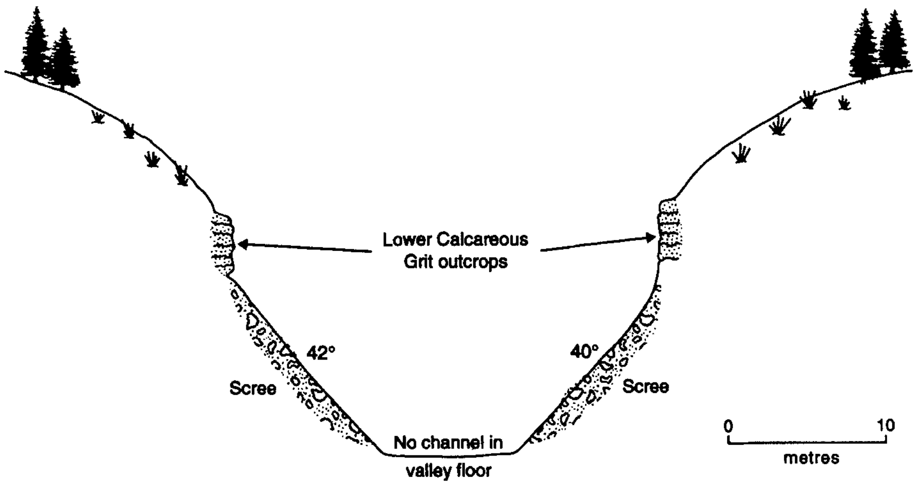

Figure 5. Cross-sectional form of the upper section of the Hard Dale Valley

are present in all valleys (Figure 2); upper valley sections above springlines have channelless sediment-filled floors (Figure 6) with no evidence of former stream flow, whilst lower sections of all valleys contain perennial streams. Spring sites are also associated with sub-horizontal zones of groundwater seepage which can be traced along the valley flanks, the amount of seepage diminishing with distance from the spring site. These seepage zones, however, are not obvious in all valleys as mass movement processes often lead to the mantling of valley flanks with soil debris which is subsequently densely vegetated. Figure 7 shows a typical seepage zone in which the bedrock above the line of seepage is comparatively dry whilst the underlying siltstone is saturated (and consequently more heavily vegetated).

Groundwater emerges along bedding planes in a 20 to 30 cm thick zone as opposed to seeping through

Figure 6. Morphology of the upper section of Breaday Gill up-valley of the spring line and zone of seepage

Figure 7. The seepage zone in Hard Dale (note: the geological hammer is situated on the line of maximum seepage)

pore spaces within the rock. Whilst rock above the seepage zone shows little evidence of substantial weathering, material below is broken down into small angular fragments up to 12 mm in diameter. The main process of rock weathering appears to be granular disintegration with break-up generally following the line of bedding planes. Rock weakening occurs in the vicinity of the seepage zone, with increased jointing and fracturing along bedding planes. This can be partly attributed to biomechanical weathering mechanisms associated with the growth of mosses and algae which colonize rock joints within the moist seepage zone. However, the extent to which plants are weathering agents or are simply exploiting pre-existing niches is unclear. The seepage zone is also frequently associated with slope failures where the hillslope above the site of groundwater emergence is undermined.

Immediately below the springline and zone of seepage the valley morphology changes, with a channel incised into bedrock commonly present (Figure 8). Streamflow below the springline is sufficiently competent to remove the products of granular disintegration and mass wasting and maintain a debris-free channel. Whilst upper sections of most tributaries are comparatively straight there is a tendency for the valley to meander below the point of spring emergence. The presence of the springline also appears to be associated with a change in the long-profile gradient of many valleys. Typical gradients for upper sections of valleys range between 7·4° and 14·8° whilst lower sections below the springline are at much gentler angles of approximately 1·5° to 2·5°. It should be noted that, except in the case of Breaday Gill, this change in long-profile gradient is not an abrupt one, but occurs over the course of the valley. Possible explanations for the morphological variability above and below spring sites will be explored in the following sections

Figure 8. Morphology of the lower section of Folly Gill, below the spring line

but appears to be mainly a product of the differential resistance of the Upper Oxford Clay and the Lower Calcareous Grit.

The major morphological differences between the valleys in this study and those of sapping and seepage erosion networks in more arid areas (such as the Colorado Plateau) occur above the amphitheatre head region and in lower valley sections below the springline. Figure 1 indicates that whilst valleys in the Hackness Hills originate relatively abruptly, a channel may be present above the amphitheatre valley head. In some valleys, such as Oak Rigg Gill, channels are cut into soil and fill material with evidence of subsurface piping. Thus, whilst it appears that the majority of precipitation recharges groundwater supplies, there is some surface runoff around valley heads. It is also apparent from Figure 1 that valleys do not maintain a constant width along their length, again deviating from observations of networks such as those of the Colorado Plateau which developed predominantly by groundwater erosion processes. These differences result from a combination of two factors. Firstly, the well-jointed rocks in the Hackness area have a lower strength compared to the well-cemented Navajo Sandstone of the Colorado Plateau (Baker, 1990) and are thus less able to maintain steep slope angles. Secondly, the consistently higher levels of annual precipitation in North Yorkshire (893 mm compared to 130–380 mm; Baker, 1990) are more likely to encourage the operation of mass movement processes which will lead to a reduction of slope angles.

Links between geology and geomorphology in Whisperdales and High Dales

In addition to morphological surveying, each of the ten main tributary valleys which form Whisperdales and High Dales were lithologically surveyed and logged. The results of these surveys and the main geological units present within each valley are shown in Figure 9. The general sequence within each of the valleys consists of shaley to flaggy clay-siltstone in lower sections (the Upper Oxford Clay, best exposed in Highdales Beck) which typically contains 3 per cent clay, 7 per cent fine silt, 20 per cent medium silt, 55 per cent coarse silt and 15 per cent fine sand (J. K. Wright, personal communication). This passes gradually upwards into the Lower Calcareous Grit which is a flaggy siltstone in its lower sections (containing 50 to 80 per cent silt and clay) but progressively changes to a silty sandstone (45 to 65 per cent fine sand) in its more massive uppermost horizons (Wright, 1983). The uppermost sections of the Lower Calcareous Grit have a particularly high silica content due to the redistribution of silica from diagenetically altered sponge spicules which, in some locations, may constitute up to 60 per cent of the rock (Hemingway, 1974; Wright, 1983).

This silicified layer is largely responsible for maintaining the level upper plateau surface (as seen in Figure 3) and, given the gentle southerly regional dip, explains why the highest point of the Hackness Hills occurs in the extreme north and northwest of the plateau. The Lower Calcareous Grit is well-jointed in all exposures and, with the exception of the uppermost silicified horizons, is highly porous.

Major fossiliferous and mineralogical marker horizons allow correlation of the sequences between the main tributary valleys. The Upper Oxford Clay and Lower Calcareous Grit are relatively fossil-poor throughout the bulk of the stream sections, although many beds in the Lower Calcareous Grit are locally highly fossiliferous. The most conspicuous fossiliferous layers consisted of 15 to 20 cm thick beds rich in the brachiopods *Rhynchonelloidella* sp. and *Pinna* sp. Mineralogical marker horizons were sections with iron oxide staining, the most distinctive of which contained sub-vertical iron oxide bands which cut across bedding planes within lower parts of the flaggy Lower Calcareous Grit. These bands were identified in six of the valley sections. In addition, distinctive horizontal and sub-horizontal iron-rich bands were identified in three valley sections and were utilized in between-valley correlation.

Insufficient ammonite specimens were found within the sequences to allow accurate identification of the change between the Upper Oxford Clay and Lower Calcareous Grit which occurs within the *Cardioceras praecordatum* ammonite subzone (Wright, 1983). Separation of the two lithologies is difficult on sedimentological grounds alone as there is only a subtle change in the rock characteristics. Comparisons with coastal sections exposing the boundary between the two lithologies are also unhelpful as the formation of the Upper Oxford Clay and Lower Calcareous Grit may have been diachronous (Wright, 1983). As a result, the lithological boundary is identified on Figure 9 by the presence of a widely correlated iron oxide stained bed below which the rock is predominantly a grey siltstone and above which a buff colour is prevalent.

On the basis of lithological logging and the observations of valley morphology it is clear that the gradual vertical change in lithology indicated by the increase in clay content towards the bottom of the section has

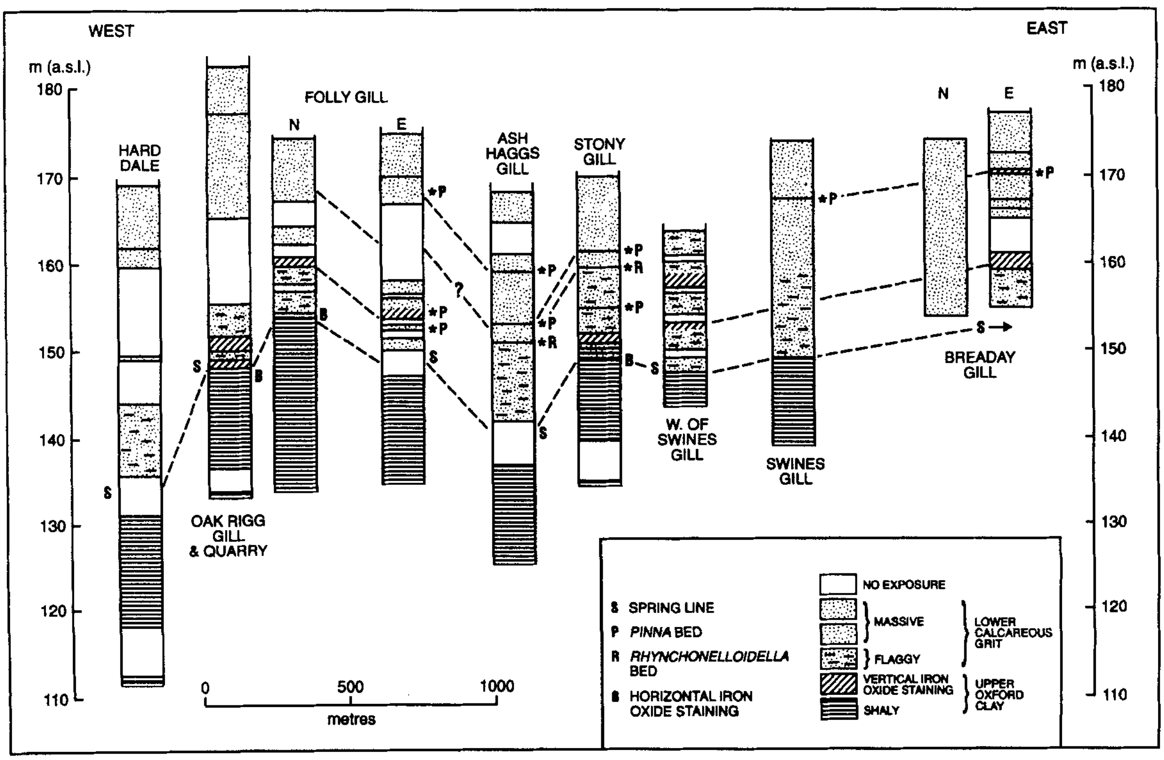

Figure 9. Geological logs of the rocks exposed within the ten stream sections cutting into the Hackness Hills showing the major variations within the Upper Oxford Clay and Lower Calcareous Grit (note: an asterisk by a lithological log indicates a fossiliferous horizon)

had an important effect on valley development. The geological logs in Figure 9 demonstrate the gentle southerly dip of the rocks in this region, indicated by the altitude of the boundary between the Upper Oxford Clay and the Lower Calcareous Grit. The change in lithology invariably either coincides with the presence of springs within the valley floors and clearly identifiable seepage zones in the valley walls (Figure 7) or occurs up to 2 m below the spring line. The altitude of these spring lines also varies between valleys, reflecting the southerly dip of the bedrock. Geological and morphological mapping were undertaken at different times of the year but there was no apparent change in the position of the spring sites between periods of site investigation nor in the discharge.

Lithological and mineralogical changes at the seepage zone

To investigate the conditions responsible for groundwater emergence, bedrock samples were collected in each of the seven valleys which contained clearly identifiable seepage zones. Samples were collected from above, within and below the zone of seepage and analysed by X-ray diffraction (XRD) in order to identify changes in sample mineralogy.

Results of XRD analyses of samples from Hard Dale, one of the High Dales tributaries, are shown in Figure 10 and Table I. This valley contains a prominent spring and associated seepage zone in the valley flank (Figure 7). Samples HD-1 and HD-2 were taken from 1·0 m and 0·5 m, respectively, above the seepage line, sample HD-3 was collected at the seepage line, whilst samples HD-4 and HD-5 were from 0·5 m and 1·0 m, respectively, below the line of seepage. The boundary between the Lower Calcareous Grit and Upper Oxford Clay was not clearly identifiable within the valley but appears to occur below the line of seepage.

The main observations which can be made from the XRD analyses are that, in all five samples, quartz is the dominant mineral present along with feldspars and micas, with variable proportions of calcite. The most remarkable result is the lack of any clay minerals within the samples. This would suggest that the zone of groundwater emergence occurs entirely within the Lower Calcareous Grit as clay minerals are only present in identifiable quantities in the Upper Oxford Clay. This would further support field observations suggesting that the boundary between the two rock types occurs below the line of seepage. It is uncertain whether illite is present in the samples as the main muscovite peaks on the XRD trace coincide with the main illite peaks. However, the analysis of samples in hand specimen clearly shows the presence of muscovite. This does not imply that illite is not present but merely that it cannot be distinguished from muscovite by XRD analysis.

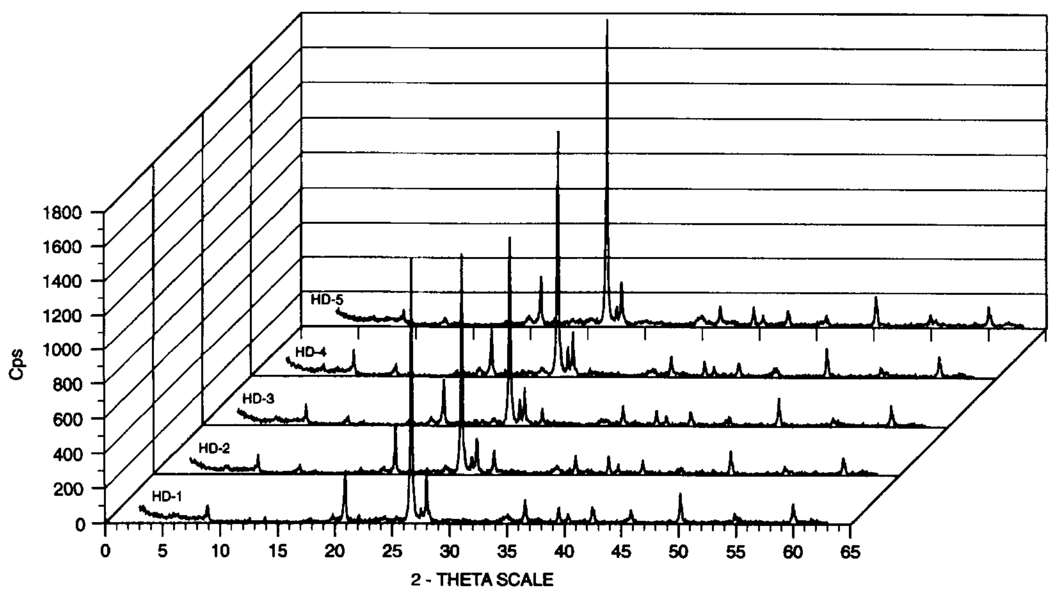

Figure 10. Three-dimensional display of XRD scans for samples HD-1 to HD-5

Table I. XRD analyses of siltstone samples from Hard Dale

Sample	HD-1	HD-2	HD-3	HD-4	HD-5
Sample position relative to seepage line	1·0 m above	0·5 m above	At seepage line	0·5 m below	0·5 m below
Minerals					
Quartz	*	*	*	*	*
Anorthoclase	*	*	*	*	*
Albite	*	*	*	*	*
Muscovite	*	*	*	*	*
Clinochlore	*	*	*	*	*
Illite	†	†	†	†	†
Vermiculite					
Chlorite					
Smectite					
Kaolinite					
Sepiolite					
Talc					
Glauconite					
Palygorskite					
Gibbsite					
Sericite					
Montmorillonite					
Calcite		*	*	*	*
Relative % calcite	0%	100%	61%	22%	9%

* Mineral present in sample
† See text

These results suggest that the increase in clay content between the Lower Calcareous Grit and the Upper Oxford Clay is not the only factor responsible for the presence of the seepage zone, which contrasts with the original suggestion of Kendall and Wroot (1924). The variable calcite content combined with the progressive overall decrease in grain size lower down the sequence may be a more important factor in controlling initial groundwater emergence. Previous analyses of the constituents of the siltstone suggest that the cementing material is predominantly silica and calcite, with increasing quantities of calcite in lower parts of the succession (Wilson, 1949). Thus, higher sections of the Lower Calcareous Grit which contain a coarser sand component are likely to have a greater pore space whilst the increase in silt lower in the sequence may reduce permeability. It is likely that the combination of reduced pore space with increasing calcite cementation provides a suitable lithological change to increase local hydrologic conductivity and cause groundwater emergence. Despite the recognition that an increase in clay content is not the only factor controlling groundwater emergence, it is highly unlikely that the close proximity of the observed seepage zones and the boundary between the Upper Oxford Clay and Lower Calcareous Grit is purely coincidental. The fact that the boundary invariably occurs up to 2 m below the seepage zone would tend to indicate that the increase in clay minerals is a major controlling factor in the overall process of groundwater emergence.

DRAINAGE DEVELOPMENT IN THE HACKNESS HILLS

From the above results, it is likely that groundwater seepage and sapping erosion played a role in the development of the Whisperdales and High Dales valleys. Indeed, observations of active weathering processes around the zone of seepage in the valley flanks suggest that sapping and seepage erosion processes appear to be a factor in contemporary valley development.

The geological setting of the Hackness Hills provides an almost ideal situation within which groundwater erosion processes can operate. The Lower Calcareous Grit provides a permeable aquifer and overlies the impermeable Upper Oxford Clay. The groundwater system is recharged on an annual basis, maintaining a series of perennial springs which, in the past, provided the basis of the water supply for the plateau-top villages of Silpho, Suffield and Broxa (Smith, 1829; Fox-Strangways, 1892). Perennial springs allow continuous or semi-continuous operation of sapping processes and headward erosion up the gentle southerly dip of the rocks. Figure 2 illustrates that valley systems are well developed on the southern side of the Hackness Hills but do not occur on the northerly flanks, despite a similar geological setting. Southerly movement of groundwater is apparently a prerequisite for the operation of groundwater sapping processes, allowing a constant throughput of groundwater to spring sites and seepage zones.

The present geological structure is a result of gentle mid-Tertiary folding which warped the Tertiary peneplain which existed in northeast England. This gentle warping is suggested by Hemingway (1974) to have initiated the centripetal drainage pattern in the Hackness Hills. Whilst dipping towards the south overall, the dips of the various lithologies are generally focused towards Hackness village. This, in conjunction with a lack of strongly developed parallel jointing, could explain why drainage in High Dales and Whisperdales has a 'stag's horn' pattern instead of the parallel drainage development commonly associated with stream networks developed by groundwater sapping processes in bedrock with a constant direction of geological strike (Howard *et al.*, 1988).

It should be stressed that groundwater erosion processes have not been the only factor in the development of the valleys in the Hackness Hills as there has almost certainly been a considerable contribution by surface fluvial activity. It would appear that sapping and seepage erosion have superimposed many morphological characteristics onto a valley system formed by surface fluvial processes. However, it is equally possible that seepage and surface erosion have operated in tandem through time, with different processes shaping different parts of the valleys. This spatial variability in process operation is clearly seen in the morphology of the various tributaries below the sites of spring emergence, where clearly defined channels are present (Figure 8) beneath zones of seepage emergence. In some cases valleys may be slightly sinuous, even when incised into bedrock, which appears to be more directly related to stream undercutting of interfluves as opposed to seepage erosion. At the present day, the morphological evidence for groundwater sapping is mainly confined to the uppermost sections of valleys above springlines whilst lower sections are more clearly altered by fluvial undercutting and mass movement processes. It would appear that groundwater sapping and seepage erosion processes are largely responsible for the headward development of the Whisperdales and High and Low Dales valleys, with fluvial action and mass movement processes dominating lower valley sections below spring sites.

This combination of surface fluvial action with seepage erosion may also provide an explanation for the origin of the free face required for the initiation of groundwater seepage. Such a free face could be provided by a pre-existing stream or depression, the origin of which could be linked to incision of sub-aerial meltwater channels which have dominated the drainage development of the Hackness area (Penny, 1974). The erosion of such meltwater channels, if this was the mechanism by which the Hackness Gorge and the lower sections of Whisperdales and Low Dales were formed, may have led to drainage incision below the level of the Upper Oxford Clay and Lower Calcareous Grit boundary. This would, in turn, have allowed the emergence of groundwater and the potential for the progressive development of the Whisperdales and High and Low Dales tributaries.

CONCLUSIONS

The results of this study, whilst largely qualitative, have a number of wider implications which tend to support the suggestions put forward by Baker (1990) regarding the operation of groundwater erosion processes under different climatic regimes and in varying lithologies. The diagnostic morphometric properties suggested to be indicative of valleys developed by groundwater erosion processes (described above) are the result of numerous detailed studies in areas such as the Colorado Plateau, where almost perfect conditions for the operation of such processes occur (Baker, 1990). However, not all valleys influenced by seepage

erosion will match these criteria. In particular, the amphitheatre valley head and near-vertical valley sides, often considered an essential feature of groundwater outflow networks (Howard *et al.*, 1988), may not be present if erosion by surface flow and hillslope processes exceeds erosion by groundwater seepage (Sakura *et al.*, 1987). This will, in part, be controlled by the climate of a region but will also be greatly affected by the local rock strength. Seepage erosion networks in drylands are often more readily identified than their temperate counterparts as there is less likelihood of contemporary surface flow and slope failure masking the influence of groundwater erosion processes. Valleys such as those of the Colorado Plateau must, therefore, be viewed as forming one end of a process spectrum with valleys developed purely by surface erosion forming the opposite end member. Valley systems such as those in the Hackness Hills would seem to fall logically somewhere between these two extremes.

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REFERENCES

Arkell, W. J. 1933. *Jurassic system in Great Britain, Parts 1 and 2*, Oxford University Press, Oxford.

Baker, V. R. 1980. *Some terrestrial analogs to dry valley systems on Mars*, NASA Technical Memo TM 81776, 286–288.

Baker, V. R. 1990. 'Spring-sapping and valley network development', in Higgins, C. G. and Coates, D. R. (Eds), *Groundwater Geomorphology; the Role of Subsurface Water in Earth-Surface Processes and Landforms*, Geological Society of America Special Paper 252, Boulder, Colorado, 235–265.

Brumhead, D. 1979. *Geology Explained in the Yorkshire Dales and on the Yorkshire Coast*, David and Charles, London.

Dunne, T. 1980. 'Function and control of channel networks', *Progress in Physical Geography*, **4**, 211–239.

Dunne, T. 1990. 'Hydrology, mechanics, and geomorphic implications of erosion by subsurface flow', in Higgins, C. G. and Coates, D. R. (Eds), *Groundwater Geomorphology; the Role of Subsurface Water in Earth-Surface Processes and Landforms*, Geological Society of America Special Paper 252, Boulder, Colorado, 1–28.

El-Baz, F., Boulos, L., Breed, C., Dardir, A., Dowidar, H., El-Etr, H., Embabi, N., Grolier, M., Haynes, V., Ibrahim, M., Issawi, B., Maxwell, T., McCauley, J., McHugh, W., Moustafa, A. and Yousif, M. 1980. 'Journey to the Gilf Kebir and Uweinat, southwest Egypt', *Geographical Journal*, **146**, 51–93.

Fox-Strangways, C. 1892. *The Jurassic rocks of Britain: Volume 1, Yorkshire*, Memoir of the Geological Survey of the UK, Eyre and Spottiswoode, London.

Gomez, B. and Mullen, V. T. 1992. 'An experimental study of sapped drainage network development', *Earth Surface Processes and Landforms*, **17**, 465–476.

Hemingway, J. E. 1974. 'Jurassic', in Rayner, D. H. and Hemingway, J. E. (Eds), *Geology and Mineral Resources of Yorkshire*, Yorkshire Geological Society, Leeds, 161–223.

Higgins, C. G. 1984. 'Piping and sapping: development of landforms by groundwater outflow', in La Fleur, R. G. (Ed.), *Groundwater as a Geomorphic Agent*, Allen and Unwin, London, 18–58.

Howard, A. D. and McLane, C. F. 1988. 'Erosion of cohesionless sediment by groundwater seepage', *Water Resources Research*, **24**, 1659–1674.

Howard, A. D., Kochel, R. C. and Holt, H. E. 1988. *Sapping Features of the Colorado Plateau—a Comparative Planetary Geology Fieldguide*, NASA Publication SP-491.

Kendall, P. F. 1902. 'A system of glacier lakes in the Cleveland Hills', *Quarterly Journal of the Geological Society of London*, **58**, 471–571.

Kendall, P. F. and Wroot, H. E. 1924. *The Geology of Yorkshire*, printed for the authors, Vienna.

Kochel, R. C. and Piper, J. F. 1986. 'Morphology of large valleys on Hawaii: evidence for groundwater sapping and comparisons with Martian valleys', *Journal of Geophysical Research*, **91**(b13), e175–e192.

Kochel, R. C., Howard, A. D. and McLane, C. F. 1985. 'Channel networks developed by groundwater sapping in fine-grained sediments: analogs to some Martian valleys' in Woldenberg, M. J. (Ed.), *Models in Geomorphology*, Allen and Unwin, London, 313–341.

Laity, J. E. 1983. 'Diagenetic controls on groundwater sapping and valley formation, Colorado Plateau, as revealed by optical and electron microscope', *Physical Geography*, **4**, 103–125.

Laity, J. E. and Malin, M. C. 1985. 'Sapping processes and the development of theatre-headed valley networks in the Colorado Plateau', *Geological Society of America Bulletin*, **96**, 203–217.
Laity, J. E., Pieri, D. C. and Malin, M. C. 1980. *Sapping Processes in Tributary Valley Systems*, NASA Technical Memo TM 81776, 295–297.
Maxwell, J. A. 1979. *Field Investigation of Martian Canyonlands in Southwestern Egypt*, NASA Conference publication 2072, 54.
Nash, D. J. 1992. *The Development and Environmental Significance of the Dry Valleys (Mekgacha) in the Kalahari, Central Southern Africa*, unpublished Ph.D. thesis, University of Sheffield.
Nash, D. J. 1995. 'Structural control and deep-weathering in the evolution of the dry valley systems of the Kalahari, central southern Africa', *Africa Geoscience Review*, **2**, 9–23.
Nash, D. J., Thomas, D. S. G. and Shaw, P. A. 1994a. 'Timescales, environmental change and dryland valley development', in Millington, A. C. and Pye, K. (Eds), *Environmental Change in Drylands*, John Wiley, Chichester, 25–41.
Nash, D. J., Shaw, P. A. and Thomas, D. S. G. 1994b. 'Duricrust development and valley evolution: process–landform links in the Kalahari', *Earth Surface Processes and Landforms*, **19**, 299–317.
Onda, Y. 1994. 'Seepage erosion and its implication to the formation of amphitheatre valley heads: a case study at Obara, Japan', *Earth Surface Processes and Landforms*, **19**, 627–640.
Peel, R. F. 1941. 'Denudational landforms of the central Libyan desert', *Journal of Geomorphology*, **4**, 3–23.
Penny, L. F. 1974. 'Quaternary', in Rayner, D. H. and Hemingway, J. E. (Eds), *Geology and Mineral Resources of Yorkshire*, Yorkshire Geological Society, Leeds, 245–264.
Pieri, D. C., Malin, M. C. and Laity, J. E. 1980. *Sapping: Network Structure in Terrestrial and Martian Valleys*, NASA Technical Memo TM-81979, 292–293.
Sakura, Y., Mochizuki, M. and Kawasaki, I. 1987. 'Experimental studies on valley headwater erosion due to groundwater flow', *Geophysical Bulletin of Hokkaido University*, **49**, 229–239.
Schumm, S. A. and Phillips, L. 1986. 'Composite channels of the Canterbury Plains, New Zealand: a Martian analogue', *Geology*, **14**, 326–330.
Shaw, P. A. and de Vries, J. J. 1988. 'Duricrust, groundwater and valley development in the Kalahari of south-east Botswana', *Journal of Arid Environments*, **14**, 245–254.
Small, R. J. 1964. 'The escarpment dry valleys of the Wiltshire Chalk', *Transactions of the Institute of British Geographers*, **34**, 33–52.
Smith, W. 1829. 'Memoir of the stratification of the Hackness Hills', in Fox-Strangways, C. *The Jurassic rocks of Britain: Volume 1, Yorkshire*, Memoir of the Geological Survey of the UK, Eyre and Spottiswoode, London, Appendix 1, 507–514.
Sparks, B. W. and Lewis, W. V. 1957–58. 'Escarpment dry valleys near Pegsdon, Hertfordshire', *Proceedings of the Geologists Association*, **68**, 26–38.
Uchupi, E. and Oldale, R. N. 1994. 'Spring sapping origin of the enigmatic relict valleys of Cape Cod and Martha's Vineyard and Nantucket Islands, Massachusetts', *Geomorphology*, **9**, 83–95.
Wilson, V. 1934. 'Synopsis of the Jurassic rocks of Yorkshire IV: the Cornbrash and Upper Jurassic rocks', *Proceedings of the Geologists Association*, **45**, 247–306.
Wilson, V. 1948. *British Regional Geology—East Yorkshire and Lincolnshire*, HMSO, London.
Wilson, V. 1949. 'Lower Corallian of the Yorkshire Coast and Hackness Hills', *Proceedings of the Geologists Association*, **60**, 235–271.
Wright, J. K. 1968. 'Stratigraphy of Callovian rocks between Newtondale and the Scarborough coast', *Proceedings of the Geologists Association*, **79**, 363–399.
Wright, J. K. 1972. 'Stratigraphy of the Yorkshire Corallian', *Proceedings of the Yorkshire Geological Society*, **41**, 325–346.
Wright, J. K. 1983. 'The Lower Oxfordian of North Yorkshire', *Proceedings of the Yorkshire Geological Society*, **44**, 249–281.